FIELD TESTS OF THE LASER INTERROGATION OF SURFACE AGENTS (LISA) SYSTEM FOR ON-THE-MOVE STANDOFF SENSING OF CHEMICAL AGENTS

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ABSTRACT

Laser Interrogation of Surface Agents (LISA) is a new technique based on short-range Raman sensing that provides standoff detection and identification of surface-deposited chemical agents. ITT Industries, Advanced Engineering and Sciences Division is currently developing the LISA technology under a cost-sharing arrangement with the U.S. Army Soldier and Biological Chemical Command (SBCCOM) for incorporation on the Army's future reconnaissance vehicles. We will discuss the field-engineered prototype LISA-Recon system, designed to demonstrate single-shot on-the-move measurements of chemical contaminants at concentration levels below the Army's requirements. Results from laboratory and field tests will be presented. Proper identification of chemical contamination requires an on-board library of high-resolution UV Raman signatures. Laboratory measurements of these Raman spectra are presented in a companion paper.

INTRODUCTION

For the past 4 years, ITT Industries, Advanced Engineering and Sciences Division, has collaborated with Brookhaven National Laboratory (BNL) on the application of Raman scattering from surface-deposited chemicals to military sensing missions. This general measurement technique has been named Laser Interrogation of Surface Agents (LISA). BNL developed a portable proof-of-concept LISA device under DOE sponsorship, the Mini-Raman Lidar System (MRLS), which successfully detected and identified a broad range of chemicals on a variety of surfaces.[1] BNL also has developed and successfully tested a larger system mounted in a van, called the Mobile Raman Lidar Van (MRLV) for detection at ranges over 500 meters.[2]

Report Documentation Page

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1. REPORT DATE **01 JUL 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**	
4. TITLE AND SUBTITLE **Field Tests Of The Laser Interrogation Of Surface Agents (Lisa) System For On-The-Move Standoff Sensing Of Chemical Agents**		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **ITT Industries, Advanced Engineering & Sciences Division, 5901 Indian School Rd., Albuquerque, NM, 87110**		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**			
13. SUPPLEMENTARY NOTES **See also ADM001523., The original document contains color images.**			
14. ABSTRACT			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **UU**	18. NUMBER OF PAGES **7**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

While LISA technology is based on the architecture of Raman lidar, it is distinct from a classic lidar system because it is specialized for the detection of substances on surfaces at short (<50 m) ranges. Despite the success of Raman lidar in measuring atmospheric constituents at kilometer distances, its ability to remotely measure airborne chemical warfare agents is problematic due to their very small Raman cross-sections.[3] At short standoff ranges, however, the tremendous increase in signal due to the $1/R^2$ effect makes Raman detection practical, even with single laser pulses.

Theoretical analysis and laboratory measurements of Raman scattering from chemical agents and compounds at short ranges have been performed by other researchers.[3,4,5,6] The MRLS, however, was the first operational standoff detection system based on the idea of short-range noncontact detection of surface contamination that was successfully demonstrated both in the laboratory and through field trials such at the 1997 New York City Intra-agency Chemical Exercise (ICE-FIELDEX).[7,8]

In September 2000, ITT and BNL cooperatively participated in the Joint Chemical Field Trials (sensor field evaluations for the Restoration of Operations (RestOps) Advanced Concept Technology Demonstration (ACTD)) at Dugway Proving Ground. ITT and BNL deployed the MRLS to Dugway and conducted a series of measurements of chemical agent simulants and actual chemical agents during a 2-week period.[9] The MRLS successfully detected and identified chemical agent simulants at stand-off distances of ~2.5 m on several different surfaces at varying concentration levels, but not down to sensitivity level required for military reconnaissance systems. This performance limitation of the current MRLS was expected, since it was designed for a broader range of applications and not optimized specifically for these tests.

The potential of the LISA technology for non-contact detection and identification of chemical agents from a rapidly moving reconnaissance vehicle has led to a cost-sharing agreement between ITT and the U.S. Army Soldier and Biological Chemical Command (SBCCOM). The objective of this joint program is to develop and demonstrate a prototype (Generation 1) LISA-Recon system optimized to meet the Army's mission requirements. This prototype LISA-Recon system has been designed to provide on-the-move detection and identification of chemical agents at surface concentrations below the required level for reconnaissance missions.

LISA technology overcomes the limitations of the system currently integrated into reconnaissance vehicles to sense the presence of chemical agents on the ground. The present system consists of a vapor-sensing mass spectrometer and a Double Wheel Sample System (DWSS), a mechanism that picks up chemical contamination from the ground while the vehicle is in motion and transfers it to the input port of the mass spectrometer. The DWSS consists of two replaceable sample wheels attached to articulated arms. While one wheel rolls along the ground, sampling the surface, the other is lifted up to the input probe of the mass spectrometer. The intense heat at the probe face vaporizes the surface material that has stuck to the part of the wheel exposed to the probe. This vapor is then brought into the mass spectrometer by its inlet vacuum and is analyzed. This system relies on chemical agents sticking to the wheel and being sufficiently volatile to be detectable by the mass spectrometer. According to reports from crews of the Fox reconnaissance vehicle during Operation Desert Storm, the DWSS is subject to damage and reduced performance on rough terrain and at high speeds.[10] This is a significant handicap during live combat. In addition, the DWSS cannot operate for reverse speeds. Once chemical contamination is detected on a wheel, it must be manually removed and stored. This is accomplished manually by an operator inside the vehicle reaching through a glove port. Hence, mapping out the boundaries of a contaminated area is time-consuming and the resolution is poor. The DWSS also requires a significant onboard supply of replacement sample wheels and a supporting logistics train. By contrast, the LISA sensor is capable of detecting liquid and solid agents of any volatility. Detection and identification occurs for each laser pulse (currently 25 times per second for Generation 1 but this can be much higher). Hence, mapping can be extremely rapid with very high spatial resolution. The autofocus system enables LISA to function on any terrain and at any speed, forward, reverse, or stationary. The sensor requires no operator intervention or replacement of expendables during a mission. Thus, LISA technology can significantly enhance the capabilities of reconnaissance vehicles.

While this paper focuses on the Generation 1 system, it is only the first phase in a multigenerational development plan. The development of a Generation 2 system has begun through additional SBCCOM funding. Generation 2 focuses on environmentally hardening key subsystems and reducing overall system size and weight. Generation 3 will be a completely militarized system. Eight Generation 4 systems will be manufactured for pre-production testing as part of the System Development and Demonstration (SDD) program.

The multi-generational LISA development effort is supported by additional funding through Edgewood Chemical Biological Center (ECBC) to perform high resolution Raman spectral measurements. Through this effort, Raman spectra and cross-sections of chemical agent simulants, interferents and other chemicals are being measured at Brookhaven National Laboratory. Raman spectra of actual chemical agents will be measured in a surety facility at ECBC. These measurements are required to develop the database of Raman signatures needed for the identification algorithm and to optimize system parameters for chemical agent detection. Due to the resonance Raman effects which occur in the ultraviolet, the existing infrared Raman spectra are inadequate for these purposes. In a companion paper in these Proceedings, high resolution Raman measurements of simulants and other chemicals will be presented.

THE LISA CONCEPT

The LISA concept is illustrated in Figure 1. A UV laser transmitter serves as a spectrally narrow light source with high irradiance. It illuminates a chemical agent deposited on a surface. A portion of the incident light is Raman scattered by the chemical compound. This light is scattered both spatially in all directions as well as spectrally into preferred wavelengths corresponding to the unique vibrational energies of the chemical. The Raman scattered light is collected by a telescope and is coupled into a dispersive optical system. In our case, the collected light passes through a Raman edge filter and is focused onto a flexible optical fiber link. At the spectrograph, the fiber link is coupled to a fiber bundle. At the output end of the fiber bundle, individual fibers are oriented linearly to form an entrance slit for the grating-based spectrograph. A focal plane array detector records the optical spectrum of the Raman scattered light. This spectrum serves as a

Figure 1. The LISA concept.

"fingerprint" for the chemical compound. An analysis computer employs pattern-matching algorithms to identify the chemical from its spectral library of known compounds.
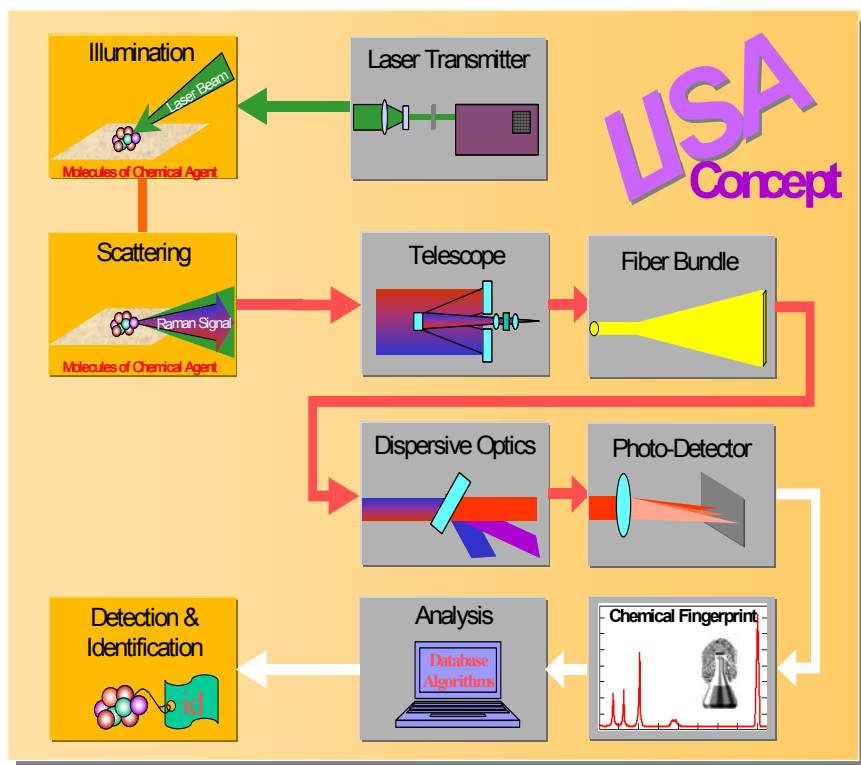
GENERATION 1 LISA-RECON PROTOTYPE DESIGN

The LISA-Recon prototype has been designed specifically to meet the need of the Army for on-the-move detection of chemical warfare agents. The LISA-Recon system consists of a sensor module which will be mounted on the Nuclear Biological Chemical Reconnaissance Vehicle (NBCRV) and stare at a fixed pointing direction at the ground. The sensor module will be connected by umbilical to an operator's console interior to the vehicle. The control and analysis computer has the capability to analyze a complicated measured spectrum for the presence of chemical agents in real-time for each individual laser pulse.

A view of the interior of the prototype sensor module is shown in Figure 2. A photograph of the sensor module with its access panel covers removed is presented in Figure 3. The sensor module housing provides environmental protection and a rigid mounting surface for the sensor subsystems. A line-narrowed excimer laser serves as the laser transmitter. This laser is very compact and can produce 20 mJ pulses at 248 nm with a 25 Hz repetition rate. The 248 nm wavelength was selected because of the increased scattering cross-section and greatly reduced interference due to background fluorescence.

Figure 2. Interior view of the Generation 1 LISA sensor module.

Beam shaping and steering optics in front of the laser insure that the laser spot on the ground has the optimal size and is centered in the telescope field of view. The beam is transmitted coaxially with the telescope.

The collecting telescope has an 8-inch primary mirror and has been designed for a stand-off distance of 1.5 m. A thorough optical analysis has revealed that the optical throughput of the telescope is very sensitive to changes in the standoff distance, as shown in figure 4. Since the reconnaissance vehicle will travel over rough terrain, a fixed focus telescope is not the optimal configuration. We have designed a "lookahead" autofocus telescope system which utilizes a rangefinder to measure the distance to ground, computes the focus position to optimize the optical throughput for the next laser pulse, and holds the telescope focus at this position. This autofocus mechanism holds the telescope throughput to within +/- 2% of its peak value at 1.5 m over the entire operating standoff range of 1.2 m to 2.2 m. It is capable of performing this task for each laser pulse, ie. 25 times a second.
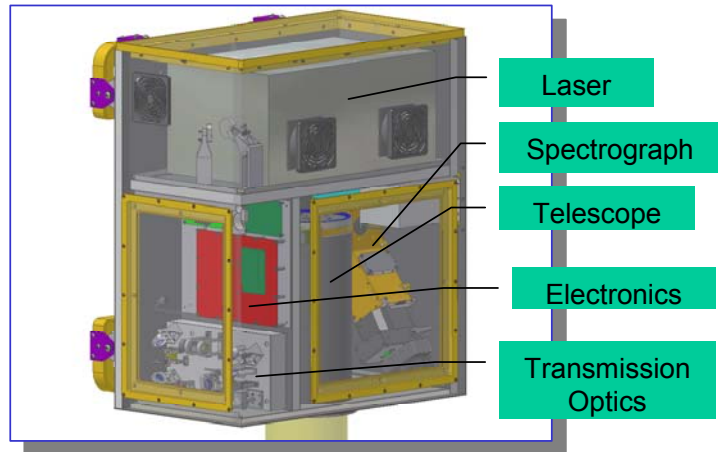

Figure 3. The Generation 1 LISA sensor module.

A Raman edge filter assembly is integrated at the rear of the telescope to reduce the elastic scatter of laser energy into the system. This assembly is fiber coupled to the analyzing spectrograph. This feature enables the subsystems to be located based upon packaging or mechanical considerations without sacrificing optical alignment tolerances. The spectrograph contains a fiber bundle which acts as a circle-to-line converter, a flat grating, and associated focusing optics. The dispersed spectrum is recorded by an intensified CCD array and is read out to the computer after every laser shot. A diagnostic video camera is mounted on the LISA sensor in order to provide further documentation of the interrogated surfaces during field testing.

Figure 4. Optical throughput vs. standoff distance for a fixed focus telescope.

The measurement spectrum is analyzed by a computerized algorithm to determine if a mixture of known chemicals is present with high confidence. The algorithm relies on an on-board library of Raman spectra of the chemicals of interest.

Major design considerations for the LISA-Recon system are: (i) laser wavelength to improve scattering efficiency and reduce fluorescence background, (ii) laser energy and system optical throughput to enable single-shot detection at the required sensitivity level and (iii) a robust chemical identification algorithm requiring under 40 msec to execute.

LABORATORY AND FIELD TESTS

A series of laboratory measurements have been performed to characterize the sensitivity of the Generation 1 sensor on non-interfering substrates and on representative surfaces (sand, gravel, vegetation, etc.). These measurements have focused on two chemical agent simulants, methyl salicylate (MeS) and diethyl malonate (DEM). Spectral features characteristic of MeS have been detected with the LISA sensor at concentration levels below those required for military reconnaissance applications. To illustrate the sensitivity of the LISA sensor to DEM and the importance of high resolution measurements at the ultraviolet wavelength utilized by the LISA sensor, we compare three Raman spectra of pure DEM in figure 5. The vertical axes are the intensities of the Raman spectra in arbitrary units. The horizontal axes are the Raman shifts in units of cm^{-1}. The top spectrum is a high resolution (4 cm^{-1}) infrared
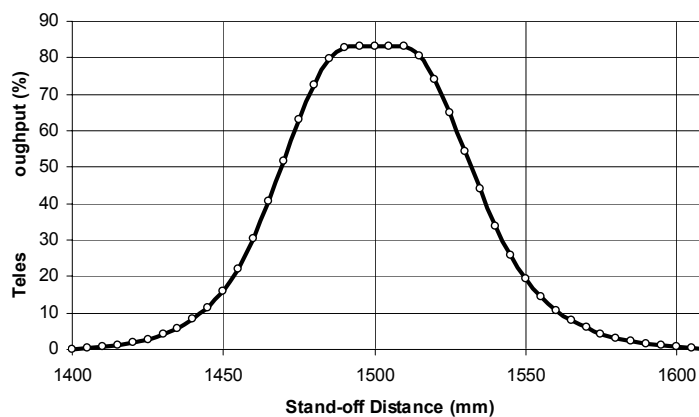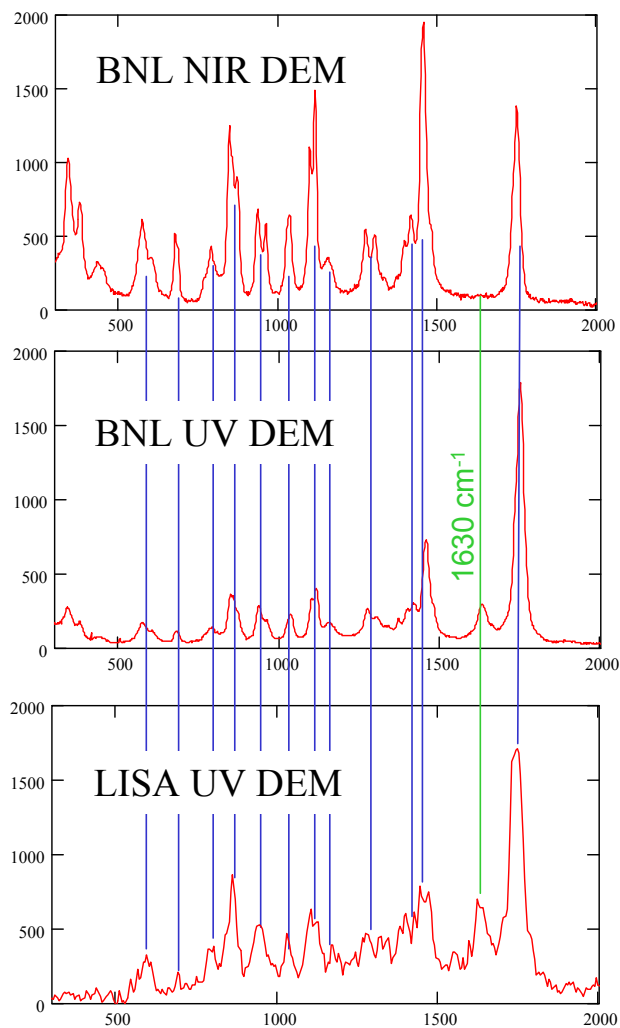

Figure 5. Comparison of BNL measurements in the IR and UV with UV LISA measurements.

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spectrum measured at BNL. The middle spectrum is also measured at BNL with high resolution but at the ultraviolet wavelength utilized by LISA. Note the appearance of a new line at 1630 cm^{-1} and changes in the relative intensities of the other Raman peaks. The bottom spectrum is a LISA measurement of a single 1.0 microliter droplet of DEM applied to a pyrex substrate and interrogated by a single 4.5 mJ laser pulse. While the resolution of the Generation 1 LISA sensor is significantly less than that of the BNL spectroscopic system, nearly all the peaks visible in the BNL spectra are also present in the LISA sensor measurement. In particular, the new peak at 1630 cm^{-1} is clearly visible. In the LISA measurement, the interfering spectra of pyrex and of the atmosphere have been removed. Unlike the BNL measurements, the LISA measurement has not been corrected for the spectral response of the sensor so that the relative heights of the spectral features are not correct.

Laboratory tests of the chemical identification algorithm have successfully shown that single and multiple chemicals can be identified with a single laser pulse with a spectral library of 10 to 20 signatures.

Preliminary field testing of the LISA sensor has been performed by mounting the sensor inside a HMMWV furnished by SBCCOM. LISA measurements were performed on-the-move on primary and dirt roads and on flat and hilly cross-country desert terrain. The targets in these cases consisted of either Teflon sheets or a layer of ethylene glycol poured on desert sand (which was totally contained within an aluminum container to prevent any contamination of the actual ground surface). In all cases, the sensor detected the chemical target.

An example of a chemical signature measured during the field testing is shown in figure 6. In this case, the HMMWV was traveling cross-country over desert terrain at ~2 mph. It drove over a sample tray holding ethylene glycol poured over sand. The single shot return from the ethylene glycol was sufficiently strong to saturate the A/D converter for the ICCD at 2900 cm^{-1}, as is evident in the figure. All the spectral peaks in this figure are characteristic of ethylene glycol. This testing was primarily qualitative in nature; the exact thickness of the chemical layer was not well characterized in the field. Future field testing will focus on quantitative measurements.

In a severe test of the look-ahead autofocus system, a Teflon target was placed on a 6" high box in order to create a sharp range transition between two sequential laser pulses. The HMMWV was driven over this test target at 5 mph. The autofocus system properly refocused the telescope and LISA detected the elevated Teflon target.
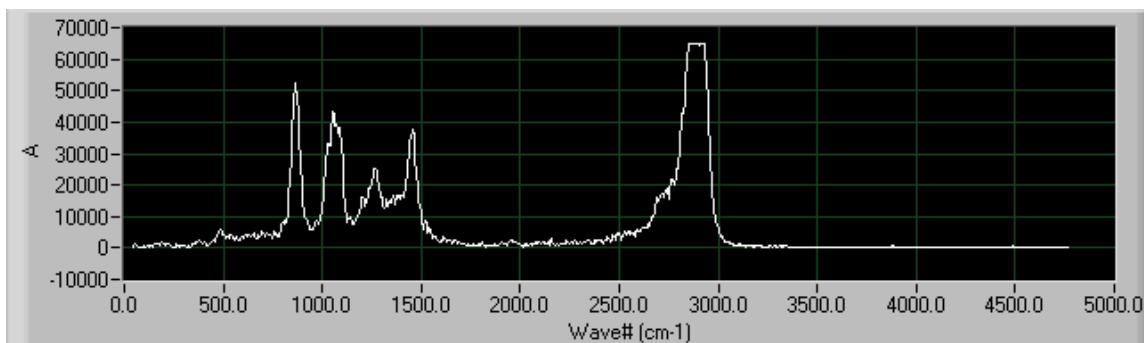

Figure 6. LISA signature from an on-the-move measurement of an ethylene glycol layer on sand.

CONCLUSIONS

The application of Raman lidar to short-range detection of surface chemicals has given rise to a new technique known as Laser Interrogation of Surface Agents (LISA). LISA provides the capability for safe, rapid, standoff detection and identification of hazardous chemicals. In the LISA approach, a high energy

laser transmitter operating in the ultraviolet illuminates the chemical. The Raman-scattered return signal is collected by a telescope, spectrally dispersed and imaged onto a focal plane array detector. The unique optical fingerprint contained in the spectrally dispersed return signal is compared to a library of Raman optical fingerprints of chemical compounds. A positive chemical agent identification is obtained using identification algorithms optimized for this purpose. This technique has been successfully demonstrated by BNL's MRLS in both the laboratory and in the field.

A joint SBCCOM-ITT development project is underway to design and test a prototype LISA-Recon system optimized to make measurements of chemical agents from a moving reconnaissance vehicle. A preliminary performance analysis of the LISA-Recon instrument has been made based upon the actual field performance of the MRLS and a careful evaluation of the system improvements incorporated into the LISA-Recon instrument. This analysis and laboratory and field results to date indicate that the sensor's sensitivity exceeds the Army's requirements. The benefits of the LISA technology for reconnaissance missions include: ability to detect agents of any volatility in solid or liquid form, autonomous operation, extremely rapid and precise mapping capability, operation at any speed and over any terrain and no need for the replacement of expendables during a mission.

ACKNOWLEDGEMENTS

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